Integrated Water Resources Modelling

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Abstract

One of the fundamental principles captured in the National Water Resource Strategy is that of the integrated management of catchments, a concept which requires the planner to consider all the possible facets of the water cycle and all likely impacts, and not to only consider the various aspects in isolation. This is not a trivial task since the interaction between the various facets can be complex. In order to understand a catchment with its multitude of water sources, multi-sectoral users, as well as the ecological requirements and water quality constraints, comprehensive water resource models are required which deal with the interaction between all these components. The socio-economic impacts of proposed developments or the implementation of the ecological Reserve also form an integral part of the decision making process and this should also form part of any integrated water resource model. In addition to this, stakeholder and public participation forms an important component of the planning and decision making process, with the result that models should strive towards simplicity, at least in the presentation of their results.

Driven by this need for an integrated water resources modelling tool, a model has been developed which meets many of the above requirements. This model, referred to in this paper as the Water Resources Modelling Platform deals with the following aspects:

- Groundwater/surface water interaction
- Water quality modelling
- Ecological requirements
- Multi-sectoral water requirements
- Streamflow reduction activities

Tools to consider the socio-economic impacts of possible management or development scenario's have been developed and it is intended to incorporate these onto this modelling platform.

A version of WReMP has been developed to run off the SPATSIM (Spatial Time Series Information Modelling) platform which provides access to wide range of water resources related models and tools, all connected to a common hydrological database. A big advantage of running WReMP from SPATSIM is it gives the user access to a graphical network builder which allows users to build their model network of dams or nodes connected by rivers or pipelines. This system will be compatible with the Pitman 2005 hydrological model, the implication being that yield analysis will be possible on all Pitman 2005 configurations, which will be available on SPATSIM. This network has GIS functionality built into it via MapObjects which will provide a powerful tool for presenting information spatially to stakeholders.

Keywords: *Integrated water resources management, water resources modelling, hydrological databases.*

1 Introduction

Much has been said and written about Integrated Water Resource Management (IWRYM), with aspects such as land use, water quality, ecological requirements and the socio-economic impacts of management options quoted in publications as the main *integration* aspects. However, less attention has been given to the modelling of the complex interaction between all these components. Numerous models are available which cover one or more of of the various aspects that influence water availability, but none deal comprehensively or seamlessly with all aspects. While this may be an unachievable ideal, model developers need to take cognisance of the changing water resource management environment in South Africa, and strive towards integrated water resources modelling.

This paper briefly discusses existing water resources models in use in South Africa within the context of IWRYM. Stemming from the perceived shortcomings of these models, an alternative modelling approach to IWRYM is described, covering most aspects which impact on the availability of water. These include water quality, groundwater use, ecological requirements, and socio-economic impacts. Integration within the water resource modelling fraternity is also discussed, within the context of utilising available databases, geographical information systems and methodologies.

2 What is integration?

2.1 Technical integration

The National Water Resources Strategy (DWAF, 2004) defines Integrated Water Resources Management as *a process which promotes the co-ordinated development and management of water, land and related resources in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital eco-systems*. It also points out the obvious to hydrologists, *that surface water, groundwater, quantity and quality are all linked in a continuous cycle – the hydrological cycle* – and that *water as a system interacts with other systems*. *Human activities such as land use and waste disposal have an impact on the quantity of water available to human use.* And most important of all, ... *water must be managed in the full understanding of its importance for social and economic development*.

From a water resources modelling point of view, IWRM presents complex technical challenges. Traditionally the focus has been on water quantity, with little consideration for the complex interaction with the various other aspects making up IWRM. While the technical aspects of water quality, land use and ecological requirements are addressed by many water resource models, the socio-economic impact of changes to existing water allocations, as will inevitably be required to meet the ecological Reserve and redress past inequities are not addressed at all. This paper describes a water resources model which is striving towards the ideal of an integrated water resource modelling tool. The aspects of IWRM which are covered in this paper are as follows:

- Water quantity
- Water quality
- Groundwater/surface water interaction
- Ecological requirements
- Land use
- Socio-economic impacts

Figure 1 presents a simplified diagram of the possible interaction between the above components of IWRM. In some cases there is a feed back loop, for example, land use activities such as irrigation will reduce the water availability to other users, while a management option to address a socio-political problem may be additional irrigation. Scenario modelling is therefore necessary, preferably in an interactive workshop environment to consider likely options.

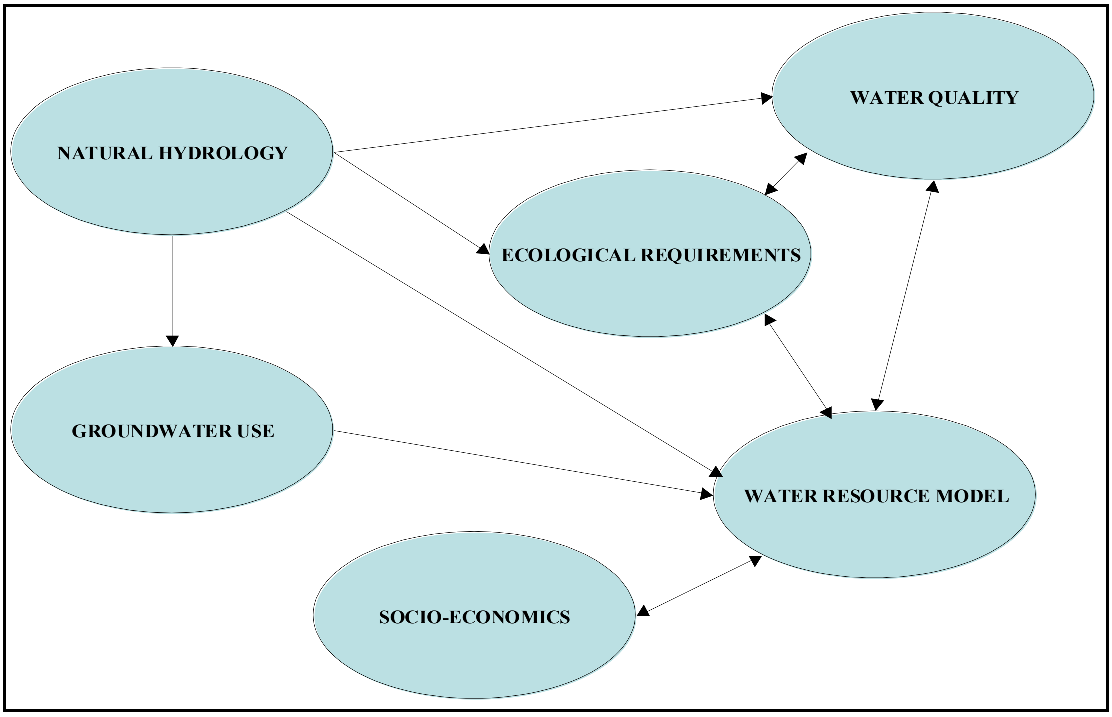

Figure 1: Integrated Water Resources Modelling

Models are available which address most of the components given in Figure 1. However, these are mostly stand-alone models, and a great deal of time and effort is expended moving and reformatting data to achieve an integrated solution. Where there is interaction or feed back between components, the use of numerous stand-alone models will be at best very time consuming. This problem was identified in Haasbroek et al 2003, where, referring to the Water Resources Yield Model (WRYM) states '*The computer assisted planning process evolved during the past two decades, and today involves multiple*

computer systems (e.g. 80+ pre- and post-processor systems in addition to the main model).' Only by integrating these so-called pre- and post-processors into a single modelling platform can progress towards an integrated water resources modelling solution be made.

Modelling integration need not necessarily imply a 'one-stop-shop' model. There are various options to achieving this modelling integration, some of which are discussed in this paper.

2.2 Information sharing

While IWRM is usually associated with the technical aspects ie water quality, land use, etc, the concept of co-operative planning is also addressed under IWRM in the NWRS, where it stated that the success of IWRM depends on co-operation amongst all relevant institutions, organisations and individuals. A crucial component of this co-operation is the sharing of data. Much progress has been made by DWAF in establishing databases for surface water hydrology, water quality, and groundwater. A comprehensive database of *registered* water use is available but a process of updating this with verified licenced use still needs to be developed. Until such time that such a database becomes available to all affected parties, the proliferation of conflicting water use databases with conflicting information will continue to sow confusion in the water resources community.

3 Water resources modelling integration in South Africa

3.1 The Water Resources Yield Model

The WRYM is a South African enhancement of the Canadian developed Acres Reservoir Simulation Programme (ARSP) (DWAF, 1998). This DOS based model has been used extensively throughout South Africa over the last 20 years. Recent enhancements to this model include developing a Windows front end, integrated graphics capabilities and a database to ultimately store the various model configurations from around the country in a common database which will be accessible to all the model users. This update is referred to as the Information Management System. While there are plans to integrate some of the 80+ pre- and post-processors referred to by Haasbroek et al (Haasbroek, 2003) into this model, as it stands now this model is still a stand-alone system not capable of interfacing with other models, other databases or any Geographical Information System (GIS).

3.2 Water Situation Assessment Model

The Water Situation Assessment Model (WSAM) was developed as a reconnaissance level water resources model for the whole of South Africa, in support of the NWRS (www.usersupport.co.za). A comprehensive dataset of water use, infrastructure and hydrology was assembled as part of this development, and while this is still very useful, it has unfortunately not been kept up to date. The WSAM database is a stand-alone system which does not integrate or interface with any other models. While the information in the model can be exported to text files which is useful, but much of the underlying data which was used in numerous pre-processors to derive annual values for WSAM is not accessible to users.

3.2 Mike Basins

Mike Basins is a commercially available water resources model used extensively throughout the world (DHI Water and Environment, 2004). It offers many of the tools required for integrated water resource modelling such a water quality, groundwater, hydrology and a comprehensive interface with GIS using ArcView. By making use of so-called COM ports, Mike Basins can interface and interact with other models. Being a commercial product, the cost of the model is not trivial, but this needs to be weighted up against the cost of developing and supporting models locally.

3.3 ACRU/HDSF

ACRU is essentially a hydrological model developed and maintained by the School for Bioresources Engineering and Environmental Hydrology with funding mostly by the Water Research Commission (Schulze, 1995). While this was orginally developed as a stand-along DOS model, it has been re-coded into an object orientated language which will facilitate integration with other similarly coded models. Work is currently in progress to integrate ACRU into a modelling framework, referred to as a Hydrological Decision Support Framework (HDSF). This modelling framework will incorporate existing models linked by a common database and integrated with a GIS for use at a planning and operational level.

3.4 SPATSIM

SPATSIM is an integrated data management and modelling software package developed by the Institute of Water Research and funded by the Water Research Commission (Hughes, 2002). It was developed using an object orientated language and includes GIS capabilities through MapObjects. The purpose of SPATSIM is to allow the efficient management, processing and modelling of the type of data associated with a range of water resource assessment approaches used in South Africa including:

- Streamflow and other time series data display and analysis
- Rainfall-runoff models (including the Pitman monthly model)
- A variety of ecological Reserve determination models

SPATSIM is used extensively in South Africa for Reserve determination, and has been selected as the preferred platform for the HDSF modelling framework referred to in paragraph 3.3. The updated Pitman model, referred to as Pitman 2005, will also be able to run from the SPATSIM platform giving the Pitman model access to a GIS system which will be used to build and visualise the hydrological network used to simulate the rainfall/runoff process.

4 The Water Resources Modelling Platform

4.1 Background to this development

The Water Resources Modelling Platform (WREMP) could be considered to be an extension and further development of the Rapid Simulation Model (Mallory, 2003) which was developed to address the needs of the NWA, especially relating to public participation in water resources planning and licencing. The basic structure of the Rapid Simulation Model as a cascading monthly simulation model has been maintained and algorithms developed to deal with complex operating rules (Mallory, van Vuuren, in progress). Complex systems can and have been modelled producing results equivalent to those of WRYM and Mike Basins. Verification of these algorithms has also been carried out using recorded inflows, outflows and reservoir water levels for three major dams in the Limpopo Province.

The approach taken to transform what was a stand-alone model into an integrated modelling tool, was to incorporate the source code of the various components to be integrated, directly into the main model. Where this was not possible for whatever reason, usually due to a lack of access to the source code, the facility to execute routines or components from the Platform is provided. The data formats are dealt within the Platform code and executing other models from the Platform becomes a simple and seamless task.

A more recent development, which is discussed in section 5, is the integration of WReMP with SPATSIM, which allows access to a much larger database, models and GIS capabilities.

4.2 Water use

In the absence of a National water use database, several tools were developed to access available water use data. The tools are for reconnaissance level analyses where no other information is available. These are discussed briefly below:-

4.2.1 Ecological Reserve

The ecological Reserve, as one of the highest priority (but non-consumptive) water requirements, must form an integral part of any water resources model if it is to be used successfully in South Africa. It is also crucial that all ecological Reserves are tested within a verified water resources model to ascertain whether the Reserve can in fact be met under current operating conditions, or if there is at least some chance of meeting the Reserve in future through curtailment of users. This reality check is seldom done and it is suggested that many of the ecological Reserves which have been determined by DWAF can never be achieved in practice.

The setting of an ecological Reserve should be the outcome of a consultative process with stakeholders, in which the socio-economic impacts of the various Reserve scenarios are evaluated. In order to achieve this, it is essential that water resources models can perform within a workshop environment, the implication being that it must be possible to determine the impacts of scenarios within, say, one minute, and present results graphically in a manner understandable to the layman. Duration curves and time series plots are commonly used methodologies but graphical output is typically prepared before a workshop and cannot be updated on the fly in response to specific what-if scenarios derived from the workshop.

The Water Resources Modelling Platform offers these integrated and workshop-capable tools related to ecological Reserves. They were applied in their earliest form to assist with the Elands River Reserve determination and are now being used in several other studies.

Integration with the SPATSIM database will achieve further efficiencies in assessing Reserves and streamlining the workshop process. This is discussed in section 5.

4.2.1 Domestic and industrial water use

The WSAM data relating to urban, rural, industrial, mining and strategic water use was exported to a text file. Using the quaternary catchment name as a key reference, a time series of water use for each of the above users can be generated for each quaternary catchment. This allows reconnaissance level simulation model to be set up very rapidly, and ensures consistency with existing National databases. However, as stated previously, this database has not been maintained and has been surpassed by the Water Registration and Management System (WARMS) and the wealth of information contained in the Internal Strategic Assessment reports (DWAF, 2004).

4.2.2 Irrigation and forestry water use

Irrigation and forestry offer more of a challenge since their water use varies with climatic conditions. Using the crop data and crop factors captured as part of WSAM's development, it is possible to generate time series irrigation requirements for each quaternary catchment. Similar routines have been developed which transform forestry information (area, species, location) into time series reduction in runoff using the information published in Gush, et al, 2003. The major difference between this forestry model and previous models is that the reduction in runoff is determined at each time step as an integral part of the modelling process and not through some external model which would need to be rerun (for every sub-catchment) should scenarios relating to forestry need to be simulated.

4.3 Groundwater/surface water impacts

A study currently in progress by DWAF referred to as the Groundwater Resource Assessment project, has resulted in, *inter alia*, a methodology to estimate the impact of groundwater abstraction on surface flow at a quaternary catchment scale and at a monthly time step (Sami, 2005). This methodology has been incorporated into the Water Resources Modelling Platform

and is currently being tested on the Middle Letaba catchment, where substantial groundwater abstractions upstream of the Middle Letaba Dam are thought to influence the yield from this dam.

4.4 Water Quality

Water quantity and quality are closely linked, and in catchments where the quality is sufficiently poor to warrant releases from dams to dilute pollutants to within acceptable concentrations, modelling of water quality within the same scenario-modelling framework of the water resources models is essential. Efforts within South Africa to achieve this are limited to the Water Resources Planning Model, which has been applied successfully to integrated (water quantity and quality) modelling of the Vaal and Olifants systems.

There are no technical barriers, however, to introducing water quality modelling into time-series simulation models hence making water quality and its impacts part of the scenario modelling process at workshops. Simple water quality modelling routines have been included in WReMP in order to achieve this and these methods were applied during the Elands River Reserve determination. The main difference between the water quality modelling in WReMP and that in WRPM is that so-called water quality drivers are included in WRPM to estimate the production of pollutants from the catchment. While this is a vigorous and technically correct solution, these water quality models are probably too slow to be used in a workshop environment. The WReMP approach has been to assume that the production of pollutants is determined through other models, such as WQ2000 (Herrold, 2004) and used as fixed input to the water resources model. Scenarios will then relate to the operation of the catchment infrastructure to maintain quality within acceptable levels rather than measures to control the source of diffuse pollutants. The WReMP water quality module allows for 5 different conservative salts introduced as point and/or diffuse sources at every node in the system. Scenarios relating to this input can be modelled as simple scaling up or down factors.

4.6 Economics

The Dublin Statement of the International Conference on Water and the Environment indicated that "*water has an economic value in all its competing uses and should be recognised as an economic good"*. There has been little agreement as to what this means and there is still debate around complementarity between aquatic ecological resource protection and economic development. Economic valuation has been seen to be controversial largely because its purpose and use have not been clearly conveyed to non-economists such as ecologists and water resource managers.

Water resources provide important benefits for improving the welfare of society and protecting the aquatic ecosystems. However, the benefits provided by natural ecosystems are widely recognised but poorly understood. It is becoming increasingly clear that natural ecosystems are under enormous pressure and the quality of the aquatic environment is deteriorating. The need to improve the welfare of society translates into increased conversion of natural ecosystems to agriculture, industrial and residential use, but also increased demand for ecosystem inputs, such as fresh water, sinks for waste, etc. Economic valuation is increasingly becoming important as a tool for decision making in balancing between competing uses, on reallocation proposals, water projects and other water policies such as resource protection which is enshrined in the NWA.

The economic valuation of water for socio-economic benefits and the valuation of ecological water requirements to sustain natural functioning of the ecosystem have not been done extensively in Reserve determinations in South Africa before. Where valuation of the ecological services and functions have been conducted, the philosophy has been to evaluate the economic value of water users as separate from the aquatic ecology.

This paper identifies that in order to ensure IWRM, there is a need for a paradigm shift in which the economy is seen not as separate from the environment, but rather as inextricably linked to it. This paradigm can be applied to the aquatic environment (see Figure 2).

Attempts to model the economic impact of decisions, in this case relating the ecological Reserve, have to date been based on the average annual volume of water supplied to a particular sector (DWAF, 2002). However, this is an over-simplification, with the real impact being a function of a number of factors such as the degree of curtailment applied to users during droughts and the duration of the curtailment. Further research is required in order to establish these functions. The intention is then to incorporate these functions into WReMP in order that the impact of various scenarios can be realistically modelled and presented in a workshop environment.

4.7 Hydrology models

Many water resources models incorporate a hydrology model within their modelling framework, and hence the natural runoff is modelled at each time step of the water resource simulation. This concept has been investigated within the context of the Pitman Model (Midgeley, 1994) and this can be achieved, but the necessity for this questioned. The natural hydrology used in water resources models is generally accepted as the best estimate of the natural flow and is seldom if ever subjected to scenario analyses. Global warming scenarios is the possible exception to this, but these type of scenarios would require much more sophisticated models that the Pitman model, which is calibrated against observed flow. Research has been carried out using the ACRU model to evaluate global warming scenarios, and it is suggested that these scenarios can easily be dealt with in a workshop as alternative pre-processed hydrologies. This concept has been tested by using alternative stochastically generated hydrologies to obtain a range of possible reservoir trajectories rather than only a trajectory relating to the historical natural hydrology.

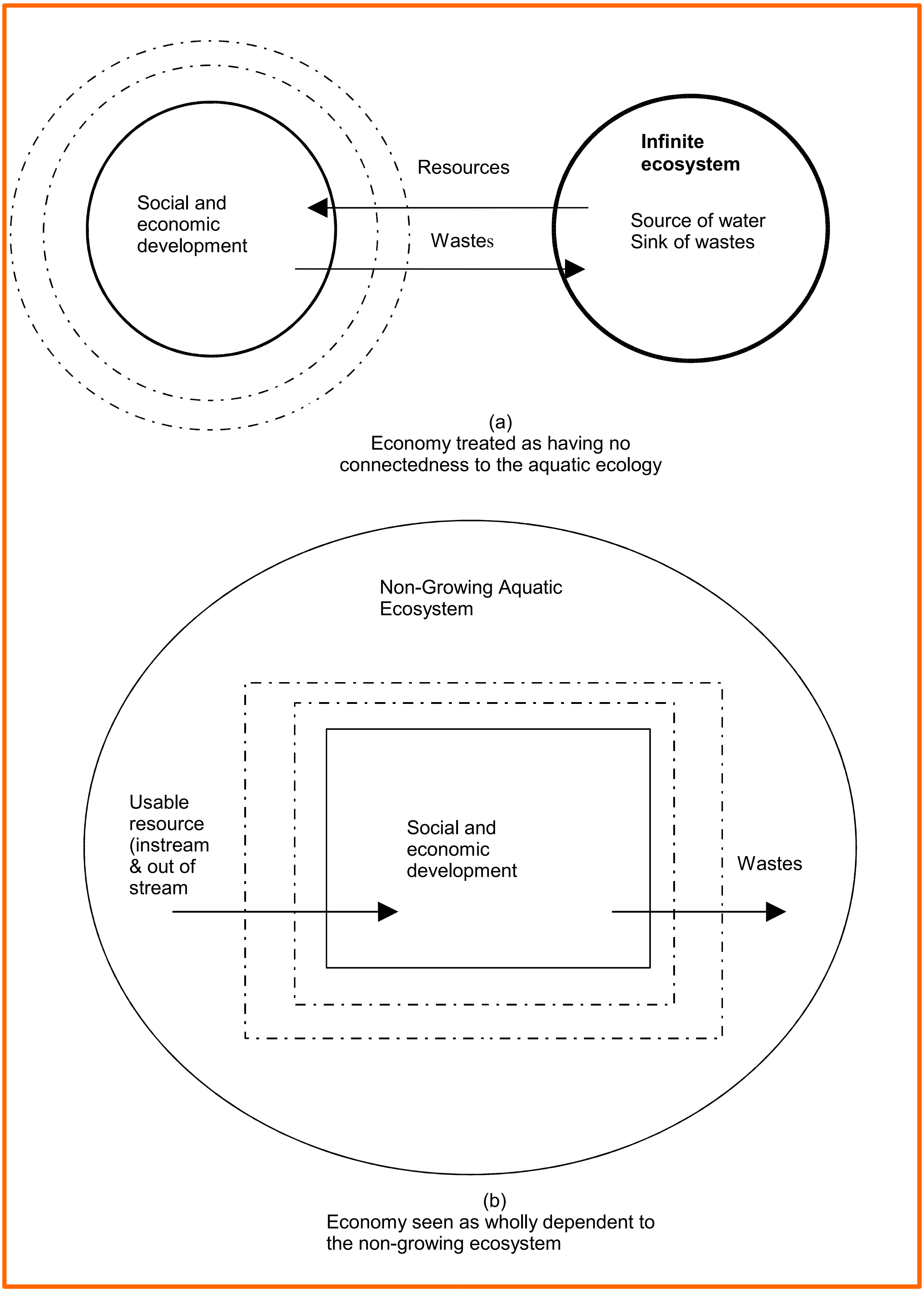

Figure 2: Integrating economics into water resources modelling

4.8 Information database

An essential requirement for successful integrated water resources modelling and management is a comprehensive database which is kept up to date and is accessible to all stakeholders and modellers. Accessibility to the database across various modelling platforms is also important so as not to marginalise modellers or stakeholders who are operating different modelling systems. It is also important to bear in mind that there are numerous models available internationally that could be successfully deployed in South Africa, and these models should not be excluded by structuring databases so as to make them inaccessible to other models.

There is not single comprehensive database in South Africa that meets all the requirements of an integrated water resources model. The best option at this point therefore seems to be to make use of a database which is compatible with as many different models as possible, in order to achieve greater integration in future. While WReMP is not currently linked to a specific database but has rather developed around accepted formats for various data structures, the way forward would appear to be to develop compatibility with the SPATSIM database, a concept which is discussed in section 5.

4.9 GIS/Visual interface

It is becoming increasingly apparent that a key component to stakeholder participation is a Geographical Information System (GIS) which can be used to display information within the spatial context of a catchment. GIS seems to have become almost a pre-requisite for water resource models and review of internationally available models (Mallory, van Vuuren, in progress) shows all popular water resources models support GIS in some form.

The development of a spatially linked visual interface is very complex, considerably more so than most water resources models, and the approach with most models has been to interface with existing GIS software and databases rather than develop separate and incompatible systems. Various options were considered in the development of WReMP, and the most cost effective and acceptable seems to be to make use of the visual interface available on SPATSIM. This is discussed in more detail in section 5.

5 Integration with SPATSIM

SPATSIM (Spatial and Time Series Information Modelling) is a software package developed by the Institute of Water Research for the Water Research Commission (Hughes, 2002). The original concept of SPATSIM was to replace modelling pre- and post-processing so as to improve modelling efficiency. This was achieved through development of a generic database and GIS spatial interface which allows almost any existing model or software to run off a common platform using data which is common to other models. This concept has been applied mainly to the ecological Reserve software and a large suite of Reserve related software is now supported by SPATSIM.

A number of recent developments have opted to develop further from the SPATSIM platform. These are the HSDF development (see section 3.3) and the Pitman 2005 model. The implication of this to water resource modellers is that all the data and software emanating from the Pitman 2005 study will be available on the SPATSIM platform.

The logical way forward is to develop a water resources yield model which can operate from the SPATSIM platform and hence make use of all the existing hydrological data (rainfall, runoff, evaporation, etc) that is currently available on this database and all the new information that will become available with the updated Pitman model. In addition, a visual interface or network builder is being developed for the Pitman 2005 model which will run from the SPATSIM platform. This is being developed using MapObjects which, while not as comprehensive and many GIS packages, offers sufficient functionality for most hydrological and water resources purposes. A version of WReMP has therefore been developed to run off SPATSIM and hence leverage off the Pitman 2005 development, rather than develop independent and possibly incompatible systems. The huge advantage of this is that, having setup and calibrated the Pitman 2005 model for the whole country, water resources yield analyses can be carried out using the identical datasets in terms of hydrology and water use. The only additional data required for a yield analysis relates to how the catchment is operated, the priorities of supply to the various users, and inclusion of ecological requirements. This could imply enormous cost savings over existing models which operate completely independently of the Pitman model and necessitate duplication in terms of network definition and the capturing water use, reduction in runoff and reservoir data.

The other advantage in integrating hydrological and yield models on a common platform is that these models can make use of identical methodologies to estimate various water uses or losses. It has always been a problem in the past that methodologies to estimate irrigation and forestry requirements in the Pitman model have not been identical to those used in the WRYM or in preparing data entry for WRYM using pre-processors. By running the two processes from the same platform sharing a common database, consistency in methodologies and results can be ensured.

The SPATSIM version of WReMP has recently been set up for the Kat River catchment in Eastern Cape as part of an integrated water resources study of this catchment, funded by the Water Research Commission. Figure 3 is a network diagram of the catchment which was set up using the network builder being developed for Pitman 2005. An interface was developed which seamlessly transforms networks, built for the Pitman 2005 model, to the structure used by WReMP, a system of nodes linked by channels very similar to WRYM and most other water resource models.

6 Conclusion

Integrated Water Resources Modelling requires that a number of interacting components be modelled simultaneously. These have been identified in this paper as water quality, groundwater use, ecological requirements and the socio-economic impacts relating the water requirements/use by various sectors. The concept of integration goes beyond this to data management and integration of related modelling systems onto a common platform sharing a common database.

The Water Resources Modelling Platform was developed as a stand-alone model which attempts to integrate the above components necessary for integrated water resources modelling onto a single platform with a common interface. This is essential if models are ever to operate successfully in a workshop environment and respond to plausible scenarios. This model has now been integrated onto the SPATSIM platform which shares many of the same modelling ideals as WReMP. This now gives users of the SPATSIM platform access to a water resources yield model with the following functionality:

- GIS visual interface using MapObjects
- Ecological Reserve
- Hydrological database
- Water use
- Streamflow reduction
- Groundwater/surface water interaction

Further development is proposed to integrate a socio-economic assessment tool into WReMP and probably onto the SPATSIM platform as well.

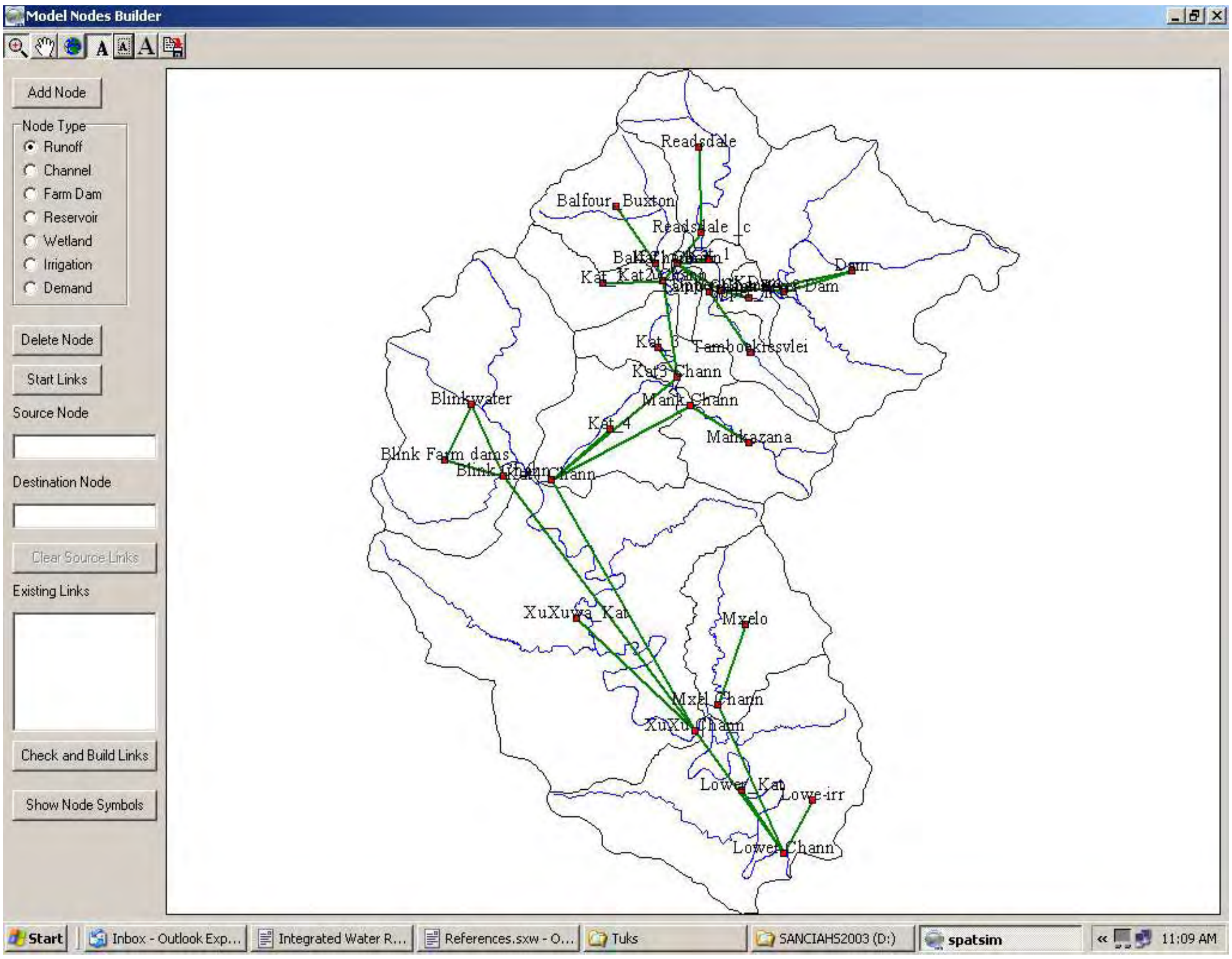

Figure 3: SPATSIM's network builder as applied in the Kat River catchment

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